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NAVIER-STOKES SIMULATION OF UNSTEADY THREE-DIMENSIONAL BLADE-VORTEX INTERACTIONS

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ABSTRACT

The unsteady, viscous, three-dimensional flow field of a helicopter rotor blade encountering a passing vortex is calculated by solving the thin layer Navier-Stokes equations by a finite-difference numerical procedure. A prescribed vortex method is adopted to preserve the structure of the interacting concentrated vortex. The test cases considered correspond to the experimental model rotor test conditions of Caradonna et al.^{1,2}

γ	=	ratio of specific heats
Γ	=	dimensionless strength of tip vortex
θ	=	pitch angle of the rotor blade
μ	=	viscosity coefficient, advance ratio
ξ, η, ζ, τ	=	generalized curvilinear coordinates
ρ	=	density
ψ	=	azimuth angle
Ω	=	angular velocity of the rotor

NOMENCLATURE

a_∞	=	characteristic velocity scale, speed of sound
C	=	characteristic length scale, chord of the blade
C_p	=	pressure coefficient
e	=	total energy per unit volume
$\vec{F}, \vec{G}, \vec{H}$	=	flux vectors
M_∞	=	free-stream Mach number
M_{tip}	=	tip Mach number of the rotor blade
p	=	static pressure
Pr	=	Prandtl number
\vec{Q}	=	flowfield vector
r_B	=	rotor reference station
R	=	rotor radius
$R(t)$	=	rotational matrix, see Eq. (7)
Re	=	Reynolds number
\vec{S}	=	viscous flux vector
u_∞	=	free stream velocity
u, v, w	=	velocity components
U, V, W	=	contravariant velocity components
x, y, z, t	=	inertial coordinates
$\tilde{x}, \tilde{y}, \tilde{z}, \tilde{t}$	=	blade attached coordinates

INTRODUCTION

The accurate simulation of the flowfield of a helicopter rotor is still one of the most complex and challenging problems of applied aerodynamics. This is true inspite of the availability of the present day supercomputers of Cray-2 class and improved numerical algorithms. The flowfield is three-dimensional, unsteady and viscous, with pockets of transonic flow near the blade tips on the advancing side and regions of dynamic stall pockets on the retreating blades. In addition, the blades also shed complex vortical wakes; the concentrated tip vortex of each blade generally passes close to the following blades. The close encounter of these (force free) concentrated vortices with the rotor blades is often the cause of unsteady load fluctuations and acoustic noise. Figure 1 shows, through a schematic, the various complexities associated with the flowfield of a typical helicopter rotor in forward flight.

The spiralling vortex sheet emanating from each of the blades of the rotor has a profound influence on the performance of the helicopter. It not only alters the effective pitch angle of the blades and thus the airloads, but also produces highly nonlinear interactions of the vortex with the rotor flowfield. This might result many times in shock induced boundary layer separation

with associated loss of lift and increased drag. An accurate simulation of the rotor flowfield, therefore, must consider the

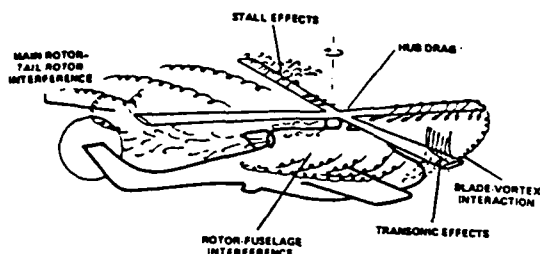


Fig. 1 Schematic of complex flowfield of a helicopter rotor

induced effects of the vortex wake including effects of blade-vortex interactions (BVI). Numerical simulation of vortex wakes is being attempted only recently after the bigger and faster computers have become available (see for example Ref. 3) and have some limited success so far. On the otherhand, much of the progress made to date in modelling the blade-vortex interaction has been hampered by the lack of the development of theoretical and/or numerical techniques to preserve the structure of the concentrated vortices in the flowfield without significant diffusion. The study of blade-vortex interaction has been the subject of numerous research papers recently.⁴⁻⁹ Among these studies, some of the methods proposed⁵⁻⁷ are not only very promising in preserving the concentrated vortices but have actually demonstrated to perform satisfactorily, atleast, in two-dimensional interactions. For example, Fig. 2 shows a comparison of experimental data of Caradonna et al.¹ with the unsteady, viscous,

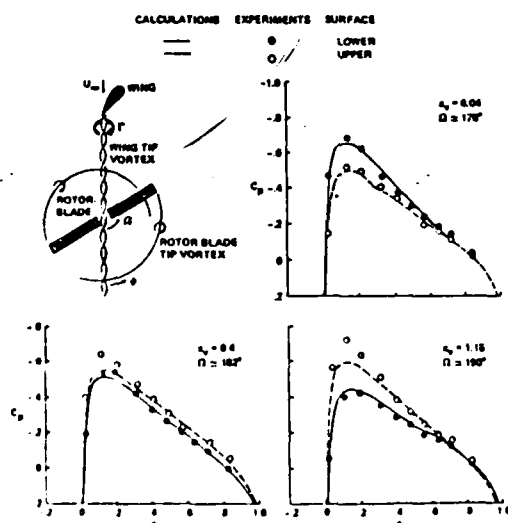


Fig. 2 Comparison of calculations and experiments for instantaneous surface pressures during a blade-vortex interaction. $M_{tip} = 0.6$, $\mu = 0.2$.

two-dimensional calculations of Srinivasan et al.⁸. This method used a prescribed vortex approach for preserving the convecting vortex.⁷ Although for the subcritical flow condition of Fig. 2, the comparison of calculations with data is excellent, at the supercritical flow conditions the shock wave dominates the flowfield and the time lag effects in shock wave growth and subsequent decay become a dominant factor. In addition, three-dimensional effects get accentuated in the presence of shock waves. Hence a two-dimensional representation of such a flowfield is inadequate as observed in the study of Ref. 8.

The purpose of this paper is to calculate accurately the unsteady interaction flowfield measured in a laboratory experiment by Caradonna et al.^{1,2} on a model helicopter rotor consisting of both the parallel and skewed blade-vortex interactions. In this experiment, the interacting vortex was generated upstream of the model rotor by means of a wing.

GOVERNING EQUATIONS AND NUMERICAL SCHEME

The unsteady, viscous flowfield calculations are performed using a recently developed thin layer Navier-Stokes code specifically written for helicopter rotor applications.¹⁰ The governing partial differential equations are the unsteady, thin-layer Navier-Stokes equations. For generality, these equations are transformed from the Cartesian reference frame (x, y, z, t) to the arbitrary curvilinear space (ξ, η, ζ, τ) while retaining strong conservation law-form to capture shock waves. The transformed equations, following Ref. 7, can be written as

$$\partial_\tau(\hat{Q} - \hat{Q}_0) + \partial_\xi(\hat{F} - \hat{F}_0) + \partial_\eta(\hat{G} - \hat{G}_0) + \partial_\zeta(\hat{H} - \hat{H}_0) = Re^{-1} \partial_\zeta \hat{S} \quad (1)$$

where

$$\hat{Q} = J^{-1} \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ e \end{bmatrix}, \quad \hat{F} = J^{-1} \begin{bmatrix} \rho U \\ \rho u U + \xi_x p \\ \rho v U + \xi_y p \\ \rho w U + \xi_z p \\ U(e + p) - \xi_t p \end{bmatrix}$$

$$\hat{G} = J^{-1} \begin{bmatrix} \rho V \\ \rho u V + \eta_x p \\ \rho v V + \eta_y p \\ \rho w V + \eta_z p \\ V(e + p) - \eta_t p \end{bmatrix}, \quad \hat{H} = J^{-1} \begin{bmatrix} \rho W \\ \rho u W + \zeta_x p \\ \rho v W + \zeta_y p \\ \rho w W + \zeta_z p \\ W(e + p) - \zeta_t p \end{bmatrix}$$

Here \hat{Q} is the flowfield vector we are solving for and \hat{Q}_0 is the solution of the Euler equations for a line vortex convecting in a uniform free stream. \hat{F} , \hat{G} , \hat{H} and \hat{F}_0 , \hat{G}_0 , \hat{H}_0 are the appropriate flux vectors for the two flows. The contravariant velocity

components U , V and W are defined as

$$\begin{aligned} U &= \xi_t + \xi_x u + \xi_y v + \xi_z w \\ V &= \eta_t + \eta_x u + \eta_y v + \eta_z w \\ W &= \zeta_t + \zeta_x u + \zeta_y v + \zeta_z w \end{aligned}$$

The viscous flux vector \hat{S} , written here in the limit of thin-layer approximation, is given by

$$\hat{S} = J^{-1} \begin{bmatrix} 0 \\ \mu m_1 u_\zeta + (\mu/3)m_2 \zeta_x \\ \mu m_1 v_\zeta + (\mu/3)m_2 \zeta_y \\ \mu m_1 w_\zeta + (\mu/3)m_2 \zeta_z \\ \mu m_1 m_3 + (\mu/3)m_2 (\zeta_x u + \zeta_y v + \zeta_z w) \end{bmatrix}$$

where

$$\begin{aligned} m_1 &= \zeta_x^2 + \zeta_y^2 + \zeta_z^2 \\ m_2 &= \zeta_x u_\zeta + \zeta_y v_\zeta + \zeta_z w_\zeta \\ m_3 &= \frac{1}{2}(u^2 + v^2 + w^2)_\zeta + \kappa Pr^{-1}(\gamma - 1)^{-1}(a^2)_\zeta \end{aligned}$$

In this equation, κ is the coefficient of thermal conductivity, Re is the Reynolds number, Pr is the Prandtl number, a is the speed of sound and J is the transformation Jacobian, whose inverse is

$$\begin{aligned} J^{-1} &= x_\xi y_\eta z_\zeta + x_\zeta y_\xi z_\eta + x_\eta y_\zeta z_\xi - x_\xi y_\zeta z_\eta \\ &\quad - x_\eta y_\xi z_\zeta - x_\zeta y_\eta z_\xi \end{aligned}$$

The primitive variables of Eq. (1), viz., the density ρ , the mass fluxes $\rho u, \rho v, \rho w$ and the energy per unit volume e , are normalized by the free stream reference quantities. The reference length scale is C and the reference time scale is C/a_∞ . The details on the metrics of the transformation $(\xi_t, \xi_x, \xi_y, \xi_z)$, $(\eta_t, \eta_x, \eta_y, \eta_z)$ and $(\zeta_t, \zeta_x, \zeta_y, \zeta_z)$ can be found in Ref. 11.

The velocity components u, v, w and the pressure, p , are related to the total energy per unit volume, e , through the equation of state for a perfect gas by

$$p = (\gamma - 1)(e - \frac{\rho}{2}(u^2 + v^2 + w^2)) \quad (2)$$

where γ is the ratio of specific heats.

In the above equations u, v , and w are the Cartesian components of the velocity in the inertial coordinate system (x, y, z, t) . In the present formulation Eq. (1) is solved in the inertial frame of reference. The inertial coordinates $X = (x, y, z, t)$

are related to the blade fixed coordinates $X_b = (\bar{x}, \bar{y}, \bar{z}, \bar{t})$ through the relation given by

$$\begin{aligned} X(x, y, z) &= R(t)X_b(\bar{x}, \bar{y}, \bar{z}) \\ t &= \bar{t} \end{aligned} \quad (3)$$

where $R(t)$ is the rotational matrix¹² given by

$$R(t) = \begin{bmatrix} \cos \Omega \bar{t} & -\sin \Omega \bar{t} & 0 \\ \sin \Omega \bar{t} & \cos \Omega \bar{t} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Here Ω is the rotational frequency of the rotor and $\Omega \bar{t}$ represents the azimuth sweep of the rotor blade.

The equation set, Eq. (1), is solved using an implicit, approximately-factored numerical scheme, developed by Ying et al.,¹³ that uses spatial central-differencing in the η and ζ directions and upwind-differencing in the ξ direction. The flux vector \hat{F} has been split into \hat{F}^+ and \hat{F}^- according to its eigenvalues and the algorithm is given by

$$\begin{aligned} &[I + h\delta_\xi^b(\hat{A}^+)^n + h\delta_\zeta \hat{C}^n - hRe^{-1}\delta_\zeta J^{-1}\hat{M}^n J - D_i|_\zeta] \\ &\times [I + h\delta_\xi^f(\hat{A}^-)^n + h\delta_\eta \hat{B}^n - D_i|_\eta] (\Delta \hat{Q}^n - \Delta \hat{Q}_0^n) = \\ &-\Delta t \{ \delta_\xi^f [(\hat{F}^+)^n - \hat{F}_0^+] + \delta_\xi^f [(\hat{F}^-)^n - \hat{F}_0^-] \\ &+ \delta_\eta (\hat{G}^n - \hat{G}_0) + \delta_\zeta (\hat{H}^n - \hat{H}_0) - Re^{-1}\delta_\zeta (\hat{S}_\zeta^n) \} \\ &-(D_e|_\eta + D_e|_\zeta)(\hat{Q}^n - \hat{Q}_0^n) \end{aligned} \quad (5)$$

The factored operators are solved by sweeping in the ξ direction and inverting tridiagonal matrices with 5×5 blocks for the other two directions. Currently, a significant part of the computational time is taken to form the plus and minus Jacobian matrices for the flux vector \hat{F} with this numerical scheme. Artificial dissipation terms (second- and fourth-order) have been added in the central differencing directions for stability reasons.¹¹ The numerical code is vectorized for the Cray-2 supercomputer.

A body conforming finite-difference grid has been used for the rectangular blade having an aspect ratio of 7 and consists of warped spherical O-O grid topology. The flowfield grid is numerically generated using the three-dimensional hyperbolic grid solver of Steger and Chaussee¹⁴ with proper clustering in the leading and trailing edge regions and in the tip region. The grid is nearly orthogonal at the surface and the spacing in the normal direction at the surface is chosen to be 0.00006C. Although most of the computations were done with a grid topology having 155 points in the periodic direction around the airfoil, and 66 points each in the spanwise and normal directions, for a total of about 700,000 grid points, some calculations were also done on a smaller grid $34 \times 99 \times 31$. The outer grid boundary is chosen to be at 10 chords in all directions for both sizes.

The boundary conditions consist of surface boundary conditions and farfield boundary conditions and are applied explicitly. At the rotating blade surface because of the noslip condition, the contravariant velocities U , V and W are set to zero. However, the time metrics ξ_t , η_t and ζ_t are nonzero as the blade (and the grid attached to it) is moving in azimuth. The density at the wall is determined by assuming an adiabatic wall condition. The pressure along the body surface is calculated from the normal momentum relation (see for example Ref. 11). Having calculated the density and pressure, the total energy is determined from the equation of state.

At the farfield boundary the flow quantities are either fixed or extrapolated from the interior depending on whether the flow is subsonic or supersonic and if it is of inflow- or outflow-type at the boundary. The characteristic velocities of the Euler equations determine the number of flow properties to be specified to control the reflections of waves from the boundaries. For the subsonic-inflow boundary, four quantities must be specified. Thus, density is extrapolated while the velocities and the total energy are specified by the free stream values. For the supersonic-inflow, all flow quantities are specified. At the subsonic-outflow boundaries, only one quantity is specified, viz., pressure is fixed. For the supersonic-outflow condition all flow quantities are extrapolated from the interior. At the plane containing the blade root the condition $\partial Q / \partial y = 0$ is imposed. The interacting vortex is assumed to have an analytical representation and is initialized as described in Ref. 7. The induced velocity due to this line vortex is calculated using Biot-Savart's Law.

RESULTS

The numerical code modified for the purpose of calculating the blade-vortex interaction has been validated against experimental data of Caradonna and Tung¹⁵ for nonlifting and lifting hover conditions at both subcritical and supercritical tip speeds in Ref. 10. The boundary layer is assumed to be turbulent in all cases considered here and an algebraic eddy viscosity model¹⁶ is used for calculating the turbulent viscosity. Figure 3 shows a typical result for a lifting hovering rotor from Ref. 10; the comparison of the calculations with the experimental data is very good.

Before considering the interaction of the rotor flowfield with a line vortex convecting with the free stream, the flowfield of a rotor in forward flight has to be computed. As noted before⁸, at the subcritical flow conditions corresponding to a $M_{tip} = 0.6$, the time lag effects and the three-dimensional effects appear negligible as shown in Fig. 4 and this is the reason that two-dimensional calculations gave excellent agreement with experiments of Caradonna et al.¹ not only for the basic rotor flow in the absence of vortex interaction, as seen in Fig. 4, but also for the blade-vortex interaction flowfield as shown in Fig. 2. It

should be noted that the experiments of parallel blade-vortex

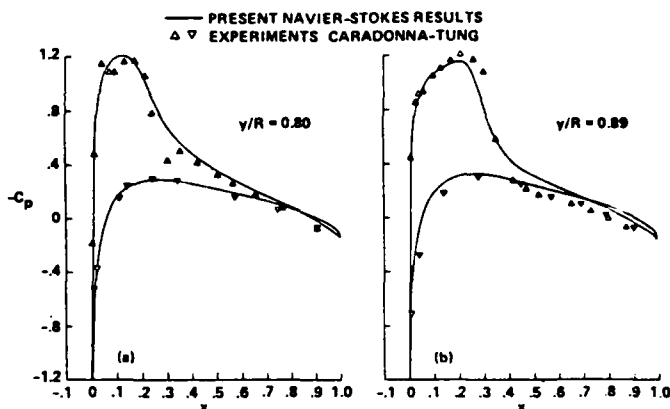


Fig. 3 Surface pressures of a lifting rotor in hover. $M_{tip} = 0.877$, $\theta = 8.0$, $Re = 3.96 \times 10^6$.

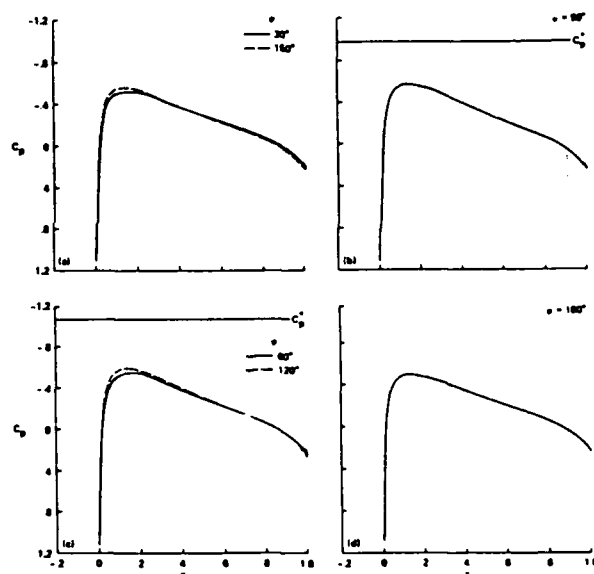


Fig. 4 Instantaneous surface pressures for a two-bladed rotor. $M_{tip} = 0.6$, $\mu = 0.2$.

interaction of Caradonna et al. were presented as test case results for validating the two-dimensional numerical calculation procedures. Although this data would provide a data source for validating the two-dimensional codes at the subcritical flow conditions, this may not be true for supercritical flow conditions as demonstrated by Srinivasan et al.³

At the supercritical tip flow conditions corresponding to $M_{tip} = 0.8$ with an advance ratio of 0.2, the basic rotor flowfield is dominated by the shock wave and earlier two-dimensional calculations showed strong flow three-dimensionality and un-

steady time-lags in shock formation and decay. Therefore, two-dimensional calculations failed to calculate accurately even the basic rotor flow. As shown in Figs. 5-6, the agreement of two-dimensional calculations with those of three-dimensional calculations and of experiment appears excellent in only the first quadrant of the rotor azimuth. In the beginning of the second quadrant, the shock wave gets very strong as the relative blade speed reaches Mach one. For this flow, the two-dimensional

assumption appears inadequate. The strengthening of the shock wave and the eventual progressive demise have strong time-lags built in to it. The flow three-dimensionality appears to be accentuated in the presence of the shock wave. Because of these features, the two-dimensional results greatly overpredict the strength of the shock wave even for the basic rotor flow (in the absence of a vortex interaction). Of course, with a vortex interaction the flowfield gets further complicated. These and other important results will be presented in the final version of the paper.

CONCLUSIONS

A numerical procedure is presented to calculate the unsteady, viscous, three-dimensional flowfields of a helicopter rotor in forward flight and blade-vortex interactions in subcritical and supercritical flow conditions. Important flow features such as time lag effects in shock growth and demise, as well as the importance of three-dimensional effects are discussed. The test cases considered here for computations correspond to the two sets of test data generated by Caradonna et al.^{1,2} on a model two-bladed rotor in a wind tunnel.

ACKNOWLEDGMENTS

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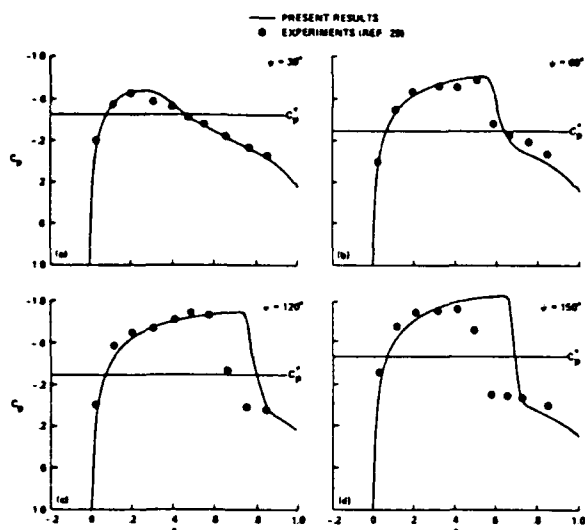


Fig. 5 Two-dimensional calculations of basic rotor flow compared with three-dimensional experimental data. $M_{tip} = 0.8$, $\mu = 0.2$.

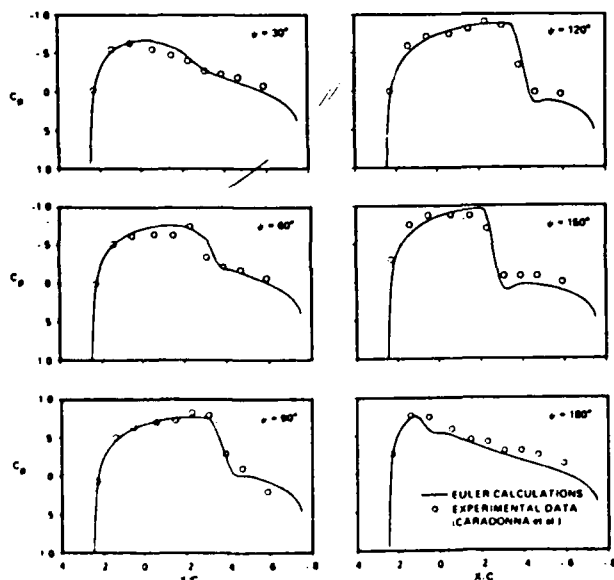


Fig. 6 Three-dimensional Euler calculations (Ref. 17) Compared with experiments (Ref. 1). $M_{tip} = 0.8$, $\mu = 0.2$.

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